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Multi-objective optimization in energy systems: the case study of Lesvos Island, Greece

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Abstract

The process of decision-making determines the choice of a possible course of action amongst a wide variety of available alternatives. The difficult point in decision-making is the multiplicity of the criteria set for judging the alternatives. The decision maker needs to attain more than one objective in achieving the final goal set, while satisfying constraints dictated by the environment, processes and resources. A multi-objective optimization methodology is applied on the island of Lesvos, Greece, where various renewable energy sources (RES) can be found and could be exploited to satisfy part of the needs of the island's economy. These resources must be examined from all aspects and a case study is performed for Lesvos that involves application of specific mathematical tools that will lead to a set of energy solutions (Pareto set). These solutions will concern the use of various energy sources that will satisfy a multiplicity of criteria (environmental, demand, cost and resource constraints). The research for this mathematical model has led to the creation of a system with two objective functions that work reversely. Considering the existing constraints, a series of solutions is derived providing decision makers the flexibility to choose the appropriate solution with respect to the given situation.

Keywords: Environmental economics; Renewable energy sources; Viable development

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Nomenclature

P_0	energy load of the conventional system
$P_{1'}$	energy load of solar collectors
P_1	energy load of photovoltaics
P_2	energy load of wind turbines
P_3	energy load of geothermal field
P_4	energy load of biomass burner
B_1	total electricity demand of the island
B_2	total thermal energy demand of the island
C_0	cost per kW h—conventional system
C_1	cost per kW h—photovoltaics
$C_{1'}$	cost per MJ—solar collectors
C_2	cost per kW h—wind turbines
C_3	cost per MJ—geothermal field
C_4	cost per MJ—biomass burner
M_0	maximum energy load of the conventional system
M_1	maximum energy load of photovoltaics
$M_{1'}$	maximum energy load of solar collectors
M_2	maximum energy load of wind turbines
M_3	maximum energy load of geothermal field
M_4	maximum energy load of biomass burner
E_0	environmental impact of the conventional system
E_1	environmental impact of photovoltaics
$E_{1'}$	environmental impact of solar collectors
E_2	environmental impact of wind turbines
E_3	environmental impact of geothermal field
E_4	environmental impact of biomass burner

Contents

1. Introduction

The main source of energy for all Greek Islands is diesel and heavy fuel oil. Even though there is an abundance of renewable energy sources (RES) such as solar, wind and geothermal ones, their use is limited. The RES are friendlier to the environment compared to fossil fuels, which contribute by far in many environmental problems that the world faces today (greenhouse effect, pollution of atmosphere, soil and water). Research has shown that the carbon dioxide is accountable for 50–66% of the rise of temperature of the surface of the earth [1]. Energy can be produced with the use of RES with minimal or zero emission of carbon dioxide. The production of energy from fossil fuels is also the main cause for the pollution of air, soil and water, as the pollutants—carbon monoxide, sulfur dioxide, nitrogen dioxide, particles, and lead—are obviously increased in amount. On the other hand, the use of RES will lead to the minimization of these pollutants.

All problems that deal with energy issues are of a multiple objective nature. The environmental impact of hydrocarbon fuels has led to a major research effort in finding other means for energy production; renewable energy systems seem to have the potential to give solutions to environmental problems. However, their availability (i.e. the density in which these sources are found) in the environment and the cost of exploiting the vast abundance of solar, wind and other RES require specific tools that will find and give a solution that satisfies all constraints. As mentioned, decision-making determines the choice of a possible action amongst given available alternatives. This multiplicity of the criteria set for choosing the alternatives is a very difficult point and decision makers need to examine more than one objective in reaching the final goal set, with respect to the satisfaction of constraints set by the environment, processes and resources.

The application of the mathematical model of multi-objective optimization in the case of Lesvos shows that available RES on the island can satisfy the local demand for electricity without the contribution of other sources e.g. diesel oil. However, the energy demand for space heating can be satisfied by combining the existing conventional system and a system operating on RES. The application of one of the derived solutions to technologies that concern the use of RES indicates that although these technologies are still under development, they can still operate at a sufficient level of efficiency. The economics study of the system shows that the present RES technologies, in spite of the high cost of purchase and installation, can be a part of the viable development of the island, since the damping time corresponds to half of the systems' total life cycle.

2. General information on the island of Lesvos

The island of Lesvos (Fig. 1) is located in the northeastern Aegean Sea with an area of 1630 km^2 and a population of 109,000. The meteorological data of the island indicate that there are fairly strong winds throughout the year (Fig. 2) and the sun shines almost all days (Figs. 3 and 4). The geothermal resources are located in three areas, with temperatures of the hot waters reaching 95 °C. Lesvos

Fig. 1. The island of Lesvos.

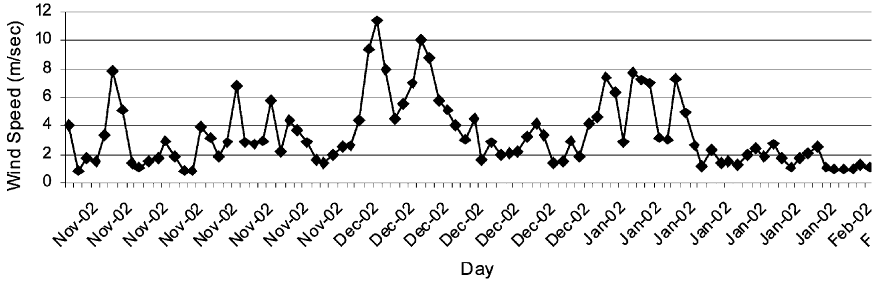

Fig. 2. Wind speed for various days in Lesvos.

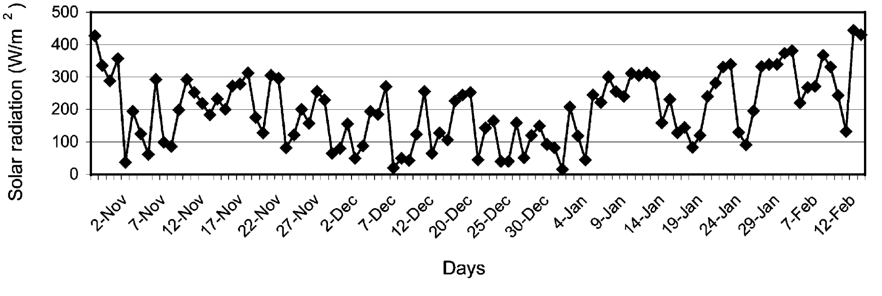

Fig. 3. Solar radiation for various days in Lesvos.

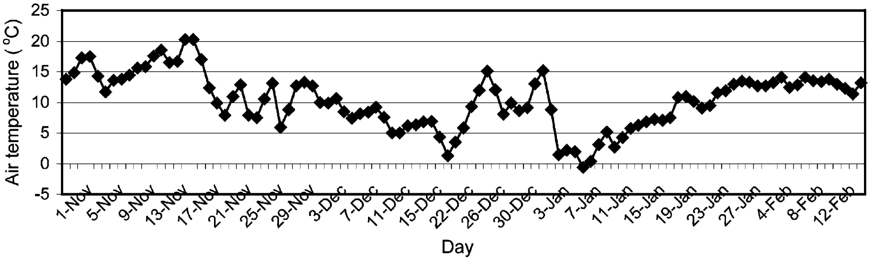

Fig. 4. Air temperature for various days in Lesvos.

produces a large amount of olive oil, which leaves a lot of biomass waste reaching 10,000 tons per year that could be utilized for heating purposes.

3. Energy system of Lesvos

The goal that was set for the sustainable development of Lesvos [2] is the achievement of an optimal solution of energy source use. A combination of the existing energy system and a system based on RES was examined in order to give a solution to the problem. The existing energy system comprises a local electricity generation station (of the Public Power Corporation, 195 MW h/year [3]), and a system of boilers for residence space heating. The current system is based on conventional fuels, something that forces the development of the island to depend on imported fuel. At the same time, the use of conventional fuel leads to the increase of pollutant emissions to the environment.

4. Energy use optimization—mathematical model definition

The inclusion of the RES of Lesvos in the existing energy system is a step that will play a significant role in the sustainable development of the island. Even though the use of RES is costly at present [4], their use will minimize the emissions that the present conventional energy generation system releases to the environment. This optimization study has two objectives: the minimization of cost and environmental effects. These two objectives are in conflict. When the cost decreases, the energy system operates more and more with conventional energy sources and environmental effects increase (higher emissions). On the other hand, as the cost increases and environmental effects decrease, the energy system operates more and more with RES. In order to simplify the problem, the needs are categorized into two sections: electricity and thermal energy needs. The electricity needs will be satisfied with the use of photovoltaics, wind turbines and the existing conventional system. The thermal energy needs will be satisfied with geothermal energy, biomass combustion and the existing conventional system.

Table 1
Possible solutions

Solution number	Conventional system (MJ)	Wind turbines (MW h)	Solar collectors (MJ)	Biomass (MJ)	Geothermy (MJ)	Equivalent CO_2 (tn)	Cost (€)
1	1,154,877,339	195,052	–	–	–	537,511	27,152,946
2	1,058,363,100	195,052	30,828,639	–	65,685,600	493,713	27,511,135
3	961,848,861	195,052	127,342,877	–	65,685,600	449,916	28,695,251
4	865,334,623	195,052	223,857,116	–	65,685,600	406,119	29,879,366
5	768,820,384	195,052	320,371,355	–	65,685,600	362,321	31,063,482
6	672,306,146	195,052	352,657,584	64,228,009	65,685,600	347,319	32,247,598
7	575,791,907	195,052	352,657,584	160,742,248	65,685,600	346,792	33,431,713
8	479,277,668	195,052	352,657,584	257,256,486	65,685,600	346,264	34,217,229
9	382,763,430	195,052	352,657,584	353,770,725	65,685,600	345,737	35,182,372

The objective functions used to model the problem are presented below as a system of equations.

Cost function:

$$\min Z_1 = P_0C_0 + P_1C_1 + P_{1'}C_{1'} + P_2C_2 + P_3C_3 + P_4C_4$$

Environmental impact function:

$$\min Z_2 = P_0E_0 + P_1E_1 + P_{1'}E_{1'} + P_2E_2 + P_3E_3 + P_4E_4$$

Electricity production:

$$P_0 + P_1 + P_2 = B_1$$

Thermal energy production:

$$P_{0'} + P_{1'} + P_3 + P_4 = B_2$$

Energy production constrains:

$$P_0 < M_0, \quad P_1 < M_1, \quad P_{1'} < M_{1'}, \quad P_2 < M_2, \quad P_3 < M_3, \quad P_4 < M_4$$

5. Results

The solution of the system of equations presented above gives a set of points that lie on a line which represents the Pareto set. As appears from the results, and due to the constraints that have been selected, the energy needs cannot be covered completely by any form of RES; only the energy needs for water heating can be covered by solar collectors. Geothermal energy and biomass combustion can cover part of the space heating needs [4,5]. On the other hand, there is complete coverage of electricity demand [6] on the island if wind turbines are used, something that does not happen if photovoltaics are used.

Table 1 illustrates a set of possible solutions. In solution 1, the electricity is covered exclusively by wind turbines, while space heating is covered by the conventional heating system. In solution 9, a part of the thermal needs is covered by RES, while the rest is covered by the conventional heating system. Table 1 also presents the costs for each case and the corresponding emissions in tons of CO_2 equivalent.

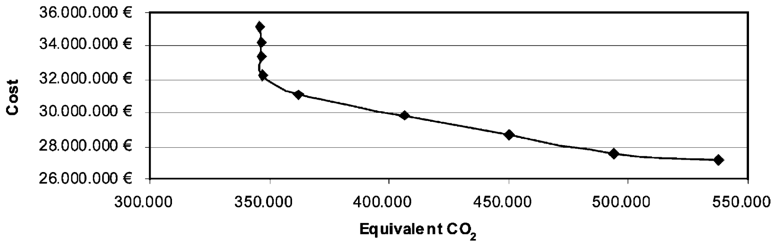

Fig. 5. Pareto set.

Table 2
Basic characteristics of the system

Renewable energy sources	Description
Solar	It is used for water heating. The area needed to cover the needs for hot water for the houses is 205,486 m^2, while the area needed for hot water for the hotels is 3570 m^2 [8,9].
Wind	It is used to produce electricity. The most appropriate wind turbine for the island of Lesvos is the type N62/1300 (i.e. 62 m blade diameter, 1300 kW nominal power). In order to satisfy the total electricity need, 43 wind turbines are necessary [10–12].
Biomass	It is used for space heating. The biomass-fuel burners can be adjusted to work on the conventional system, so that only replacement of the conventional burners is needed for the new technology to work. The olive production of the island can provide heat for 2582 residences [13–16].
Geothermal	It is used for space heating. A pipe system can be created in order to transfer the geothermal fluid to the residences. The energy can be exchanged with a closed loop fluid that can work inside the residence. This can easily be adjusted to the conventional system that already exists [17–21].

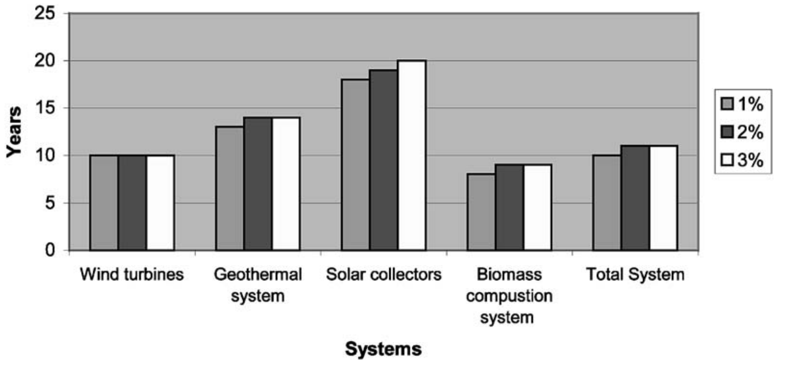

Fig. 6. System payout time.

Fig. 5 shows a diagram of possible solutions, from which it can be seen that solutions 6–9 correspond to almost equal CO_2 emissions [7], but there is a significant difference in cost. Thus, among solutions 6–9, solution 6 can be selected as it has almost the same emissions as the others but much lower cost. Something similar happens with solutions 1 and 2. In this case, the cost is almost the same but there is a large difference when comparing the emissions. That is why solution 2 is preferable to solution 1.

Table 2 shows the basic characteristics of the system. Solution 9 has been chosen because it is the solution with the highest penetration of RES into the energy production system.

The calculation of the payout time for solution 9 shows that the whole system can be paid out in 10–11 years, with an interest rate of 1–3%, which is a quite satisfactory period, considering that each system can be used for a minimum of 20 years. Fig. 6 shows the payout time for each system and for the total system for three different interest rates, 1, 2 and 3%.

6. Conclusions

The latest developments in RES technologies show that they constitute an alternative source of energy. The attributes of RES systems in combination with the low cost of maintenance make them even more attractive to use. The implementation of a system operating with RES in the island of Lesvos showed that it is not possible to replace the existing conventional energy system completely; however, it can be replaced partially. Specifically, RES can be used to cover the needs for electricity and for hot water, while they can be used in combination with the existing system for space heating.

The construction of a mathematical model in order to assist in achieving optimal use of the energy sources indicated that wind turbines can be used to cover electricity demands, and solar collectors can be used to satisfy the needs for hot water,

while geothermal energy and biomass can assist in covering space heating demands.

The cost of the technologies is judged satisfactory because the time of settlement for the total system is almost 11 years for a 3% interest rate. Thus, RES systems are profitable, since they have a life time of 20–30 years.

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